CRITICAL POINTS AND TECHNICAL APPROACH IN THE E-OSPF TIME SYNCHRONIZATION AND PREDICTION ACTIVITIES

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Abstract

Accurate satellite clock predictions are essential for navigation satellite systems. The user positioning and integrity performances are highly dependent on the level of accuracy that can be achieved when the clock estimation and prediction techniques are applied to the generation of the navigation information.

This article is aimed at presenting the latest timing approaches prototyped in the E-OSPF (Experimental Orbitography and Synchronization Processing Facility), and the obtained results, related to the clock estimation technique, the clock prediction fitting strategy, and specific solutions designed for particular Galileo system clock features.

Regarding the clock estimation technique, the OD&TS (Orbit Determination and Time Synchronization) E-OSPF SW module implements an algorithm that allows the existence of a backup time reference to be used in case of lack of observability from the master PTF (Precise Timing Facility). This is particularly useful in the IOV (In-Orbit Validation) configurations, which will allow the verification of the proper functioning of the overall system before entering the FOC (Full Operation Capability) phase.

The clock prediction fitting strategy currently implemented in the E-OSPF SW consists of estimating the zero-order clock prediction parameter with a reduced set of clock offsets containing the final epochs in the estimation arc, whereas the first-order clock prediction parameter is computed by fitting the clock offsets in a larger time period, typically as long as the estimation period. This strategy has been demonstrated to be successful with GPS data, and is now being tested for real and simulated Galileo data as well.

The fulfillment of the stringent requirements defined for the Galileo system functionality and performances imply that planned and unplanned clock events such as clock switches and resynchronizations, or clock phase jumps, among others, have to be managed by the E-OSPF in such a way the system accuracy, integrity, and availability are preserved.

1. INTRODUCTION AND BACKGROUND

Navigation Satellite Systems performances are based on the capability of the system to provide accurate ephemeris and precise clock bias predictions to the users.

In order to generate these products, the Navigation Satellite System needs to accurately know the satellite

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14. ABSTRACT
Accurate satellite clock predictions are essential for navigation satellite syst ems. The user positioning and integrity performances are highly dependent on the level of accuracy that can be achieved when the clock estimation and prediction techniques are applied to the generation of the navigation information. This article is aimed at presenting the latest timing approaches prototyped in the E-OSPF (Experimental Orbitography and Synchronization Processing Facility), and the obtained results, related to the clock estimation technique, the clock prediction fitting strategy, and specific solutions designed for particular Galileo system clock features. Regarding the clock estimation technique, the OD&TS (Orbit Determination and Time Synchronization) E-OSPF SW module implements an algorithm that allows the existence of a backup time reference to be used in case of lack of observability from the master PTF (Precise Timing Facility). This is particularly useful in the IOV (In-Orbit Validation) configurations, which will allow the verification of the proper functioning of the overall system before entering the FOC (Full Operation Capability) phase. The clock prediction fitting strategy currently implemented in the E-OSPF SW consists of estimating the zero-order clock prediction parameter with a reduced set of clock offsets containing the final epochs in the estimation arc, whereas the first-order clock prediction parameter is computed by fitting the clock offsets in a larger time period, typically as long as the estimation period. This strategy has been demonstrated to be successful with GPS data, and is now being tested for real and simulated Galileo data as well. The fulfillment of the stringent requirements defined for the Galileo system functionality and performances imply that planned and unplanned clock events such as clock switches and resynchronizations, or clock phase jumps, among others, have to be managed by the E-OSPF in such a way the system accuracy, integrity, and availability are preserved.

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positions and the offsets of their on-board clocks with respect to the system time reference. This is done by means of an OD&TS (Orbit Determination and Time Synchronization) process. The generated navigation products have to be uploaded to the satellite for delivery to the users via the "navigation message," which contains the satellites' ephemerides and clock bias predictions that enable the user to accurately compute its position at any given time within the navigation message validity interval.

Atomic frequency standards, because of their high accuracy and stability, need to be placed both on board the satellites and at the tracking stations. If it is the case that the system time reference is defined by a certain station clock, as in Galileo, where the Galileo System Time (GST) is given by the PTF (Precise Time Facility), very high quality frequency standards are specially required for the PTF clocks, since they are going to be used for:

- setting the system time reference,
- computing the time offsets of the system clocks, particularly those onboard the satellites, with respect to the system time reference, and
- keeping the system time aligned and calibrated with respect to UTC (Universal Time Coordinated)/TAI (International Atomic Time).

In Galileo, the elements that are in charge of these tasks are the PTF and the OSPF elements, respectively. GMV is responsible for the design and the development of the latter. The OSPF, by means of an OD&TS process, based on a least squares with *a priori* information filter approach, uses the tracking measurements collected by the GSSs (Galileo Sensor Stations) network for computing the orbit and clock parameters. These estimations are then used for generating the navigation messages. The quality of the OSPF navigation products depends mainly on:

- the quality of the input measurements,
- the accuracy and stability of the system clocks,
- the OD&TS process accuracy,
- the suitability of the prediction strategy, and
- the navigation message suitability, from the accuracy point of view, including discretization errors.

The E-OSPF is a non-real-time experimental platform aimed at prototyping the navigation algorithms at the OSPF, as a means to minimize the risk in many critical performance and design aspects of the operational platform. The Galileo E-OSPF platform has been designed so as to fulfill the performance requirements, for both FOC and IOV phases, in terms of accuracy, integrity, and availability, and the stringent operational constraints that will be present in the operational SW, such as the processing time and memory limitations of the operational processing platforms.

The E-OSPF experimentation and performance obtained results, some of which are presented in this article, provide clear and reliable evidence of the final performance that is expected to be obtained with the real-time operational OSPF.

GMV has been involved in the E-OSPF design and development over the last few years, as one more step in a series of projects and studies related to the Galileo navigation concepts:

- Galileo Early Trials, an experimentation project carried out in the frame of the definition of the OD&TS algorithms for Galileo
- GSTB-V1 (Galileo System Test Bed) E-OSPF, which was launched in preparation for the development of the Galileo system, as a preliminary experimentation platform aimed at carrying out OD&TS (Orbit Determination and Time Synchronization) and SISA (Signal in Space Accuracy) tests

- GSTB-V2 E-OSPF, which is the evolution of its counterpart in the GSTB-V1, and aimed at obtaining the best performances with the experimental GIOVE satellites.

One of the main differences between the Galileo E-OSPF and the GSTB-V2 projects with respect to the previous ones is the fact that they have developed SW elements specifically conceived for being able to process Galileo input data, simulated, real, or both. The earlier analyses had benefited from the similarities of GPS and Galileo systems in terms of OD&TS (similar orbit dynamics and navigation signal), which, after certain extrapolation activities, allowed the first assessments of the performance expected to be finally obtained for Galileo.

This article is aimed at presenting the latest timing approaches prototyped in the OSPF, and the results obtained related to the clock estimation technique, the clock prediction fitting strategy, and specific solutions designed for particular Galileo system clock features. The results presented represent one more step in the characterization of the Galileo clock and navigation expected performance.

2. CLOCK ESTIMATION

ODTS ALGORITHM REVIEW

The ODTS algorithm computes the orbit estimation and prediction plus the clock estimation. It is based on a weighted least-squares with an *a priori* information filter, which updates simultaneously the orbit and clock parameters. The observables are the undifferenced pseudo-range smoothed code and carrier-phase measurements coming from the PPV (preprocessing and validation) algorithm. Note that, among other tasks, PPV performs an iono-free combination of the observations from the two input frequencies.

The process can be summarized as follows:

1. Orbit integration: Given a satellite position and velocity at a certain starting epoch, an orbit is produced on the basis of dynamic information by numerical integration of the equations of motion of the satellite. Once a satellite orbit has been computed, the numerical integrator solves the so-called "variational equations" which determine the time evolution of the partial derivatives of the satellite position with respect to the estimated dynamical parameters (initial position and velocity of the satellites, and radiation pressure model coefficients). The orbit integration uses very precise models to compute the satellite acceleration, plus an empirical model to correct deviations from the configured SRP model and to absorb residual forces such as albedo, infrared radiation, etc.

2. Measurement modelling: For the sampled epochs within the estimation period, each tracking observation is reconstructed, using the known station position, the satellite position coming from the integrated orbit, and the tropospheric zenith delay at each sensor station, as follows:

$$\rho_{EXP} = \left\| \vec{x}_{GSS} - \vec{r}_{SAT} \right\| + b_{GSS} - b^{SAT} + D_{TROPO} + c\Delta t_r + \delta t_{REL}$$

where d is the geometric range; b_{GSS} and b^{SAT} are the GSS (Galileo Sensor Station) and satellite clock biases; δt_{rel} is the relativistic correction to the satellite clock; and D_{Tropo}; and $c \cdot \Delta t_r$ are the corrections to the travel time due to the tropospheric delay and relativistic effects, respectively. When the observable is carrier phase, the formula is slightly different:

$$\varphi_{EXP} = \left\| \vec{x}_{GSS} - \vec{r}_{SAT} \right\| + b_{GSS} - b^{SAT} + D_{TROPO} + c\Delta t_r - Amb\,,$$

where Amb is the ambiguity of all the phase measurements in the same satellite pass. This module uses accurate physical models, as the IERS 2003 conventions for the tidal uplift of the stations. It also computes the partial derivatives of the reconstructed measurements with respect to the estimated parameters, and the measurement residuals (difference between the actual and the reconstructed observation).

3. Parameter estimation: The weighted sum of the squares of all available residuals is minimized by estimating corrections to the various model parameters in a least-squares sense. It is based on the partial derivatives with respect to the estimated parameters computed above.

The estimated parameters are:

- Initial position and velocity of all satellites
- Solar Radiation Pressure model coefficients of all satellites
- Instantaneous satellite and station clock offsets with respect to a certain fixed reference time
- Tropospheric delay parameters (one for each 2 hours interval), for all stations
- Pass-dependent biases in carrier-phase measurements (ambiguities)
- Earth Rotation Parameters: Xp, Yp, and (UT1-UTC) (optional).

This sequence is repeated several times to converge to the solution.

ODTS CLOCK ESTIMATION

A satellite or station clock is supposed to be a realization of its local time, but in fact it has a bias with respect to the time which a perfect clock synchronized with TAI or other reference would provide: $\tau = t + b$, where τ is the time given by the clock, t is the exact time, and b is the clock bias. Note that in the case of the satellite, the relativistic effects have been removed, so that it can be treated as a clock on the Earth's geoid.

In fact, the biases appearing in the measurements reconstruction do not correspond to the real clocks, but to something called "apparent clock," which is the clock seen in the measurements. This is the result of the real clock itself plus some hardware delays, both in the satellites and the GSS cases. In this sense, the underlying clock can be excellent, but if the hardware biases are not well under control, the final result will show a degraded stability. The hardware delays are channel/frequency dependent, so the "apparent clock" is not unique, but has a different value for each channel. Then, as ODTS processes iono-free combinations of pairs of measurements, the biases estimated by ODTS are the "iono-free" combination of the "apparent clocks" of the processed channels.

Since the measurements are undifferenced, they are affected by the bias of the satellite and GSS clocks with respect to the reference time, as expressed by the previous equations.

The clock biases are estimated in the filter, as are the rest of parameters. However, there is a peculiarity that needs to be considered. The ODTS process is hardly sensitive to a change in the reference time: that is, if all the clock biases are modified by the same offset, the residuals will not change. This means that the estimation method is not able to fix the global reference, the associated system of equations being degenerate. The solution adopted is to use the clock of a GSS as reference, constraining its bias to zero. So what is finally estimated is the clock difference of all stations and satellites with respect to this reference clock.

The GSS clock reference is expected to meet stringent requirements on the behavior of its clock. In the Galileo project, there will be two GSSs that can be taken as reference (PTF). The idea behind is to use one of them nominally (master PTF), but to fix the second one as reference (slave PTF) when the first is not available, as explained in the following section.

USE OF TWO CLOCK REFERENCES

In a nominal scenario with the full satellite constellation (either GPS or Galileo), it is usually sufficient to constrain the master PTF clock to have a null bias in the estimation. To be precise, this strategy resolves the reference ambiguity of all the clocks connected to the master PTF at a given epoch, where "connected" means that there is a path of measurements from some GSS or satellite clock to the master one (for instance, a GSS has a measurement to a satellite i, which at the same time sees the master clock; then the GSS clock is "connected" to the PTF). In normal conditions, all the clocks are connected to the master PTF. Nevertheless, there are situations where some clocks are not connected to the master, either because it has no measurements at all, or because there are more than one group of clocks connected to each other but not to the other groups.

To be robust against these degenerated situations, the ODTS algorithm uses the slave PTF whenever there are clocks that cannot be referred to the master PTF. The Clock Prediction algorithm is informed of which clock offsets have been estimated with respect to the master PTF and which ones with respect to the slave PTF.

IOV CASE

In the ODTS process based in GSS measurements, the clock biases of each satellite and station are estimated at each measurement epoch. Note that the estimation of the GSS clock offsets (plus, to a lesser extent, that of the tropospheric zenith delays) ties together the orbit and clock determination of all the satellites. The consequences are mainly two for IOV scenarios, where only four satellites are available:

- Lower orbit and clock estimation accuracy. For each observations/clock epoch, the available measurements give the estimation of the satellite and GSS clock parameters at that epoch (plus a contribution to the estimation of the satellite dynamic parameters, the tropospheric zenith delay and the phase ambiguities). For a small number of satellites, it turns out that the ratio of available measurements over the number of clock parameters is lower. Hence, the expected accuracy is also smaller.
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- Very often, the master PTF does not track the four IOV satellites. In the previous section, we have seen how to use a different PTF in those circumstances. The problem is that if the two PTFs are located close to each other, it is basically useless, since they observe more or less the same satellites at the same time. The solution implemented is to allow a satellite clock to work as slave in the IOV case, so that there is always a reference available.[1]

With the use of a satellite slave clock, the IOV scenarios can be processed without losing any data. The Clock prediction algorithm will receive the information of what clock biases are computed with respect to the master PTF or the slave satellite clock. The task of the Clock Prediction algorithm is to transform

[1] A small difference with a real PTF is that the satellite clock can have big offsets, which would lead to errors in the measurement reconstruction. So the slave satellite clock is not set to zero, but to the values of a model made from the satellite clock estimation performed in the epochs where it is seen by the PTF. This model does not need to be very accurate; the accurate one will be computed by Clock Prediction.

these clocks referred to the slave into clocks referred to the master PTF; a linear or quadratic model, obtained from the value of the satellite clocks in the epochs where they are referred to the master PTF, gives the transformation. Then the user does not see the internal management of the clock reference.

3. CLOCK PREDICTION

CLOCK BIAS PREDICTION STRATEGY DEFINITION

The main objective of the clock bias prediction algorithm is to compute the parameters of the satellite clock predictions models that will be integrated in the satellite navigation messages.

The fitting strategy initially designed for being implemented in the OSPF SW consisted of estimating the clock phase offset prediction parameter (af_0) with a reduced set of clock offsets corresponding to the final epochs in the estimation arc, whereas the clock frequency parameter (af_1) was to be computed by fitting the clock offsets in a larger time period, typically as long as the estimation period. This approach had been defined as an output of an experimentation activity carried out with the GSTB-V1 E-OSPF, with real GPS data, as part of the preliminary experimentation activities aimed at supporting the design of the navigation algorithms to be implemented in the OSPF SW. The mentioned strategy was demonstrated to be suitable for GPS Block IIR satellites (rubidium clock onboard), and was to be tested also for real and simulated Galileo data.

However, in the course of the OSPF design activities, it was pointed out that, due to the fact that the GPS and the Galileo onboard clocks do not behave in the same manner, the initially designed strategy might be not fully suitable for the Galileo clock predictions. There is a difference between GPS and Galileo, based on the fact that the Galileo satellite clock specifications allow a certain frequency drift component (af_2), higher than the observed one for the GPS satellites. Experimentation carried out with the GSTB-v2 E-OSPF SW has shown that this stronger frequency drift behavior is not only allowed by the specifications, but can really be observed in the behavior of the onboard GIOVE-A satellite clock.

The following subsections describe, in more detail, the main steps in the evolution of the clock prediction strategy definition.

Step 1: Galileo Early Trial Experimentation

Clock predictability was first investigated making use an already existing SW and a set of analysis tools developed by GMV. These tools, used with a moving fit and prediction windows strategy, allowed the fitting of a model to the obtained clock estimations which was then used for generating the clock predictions. These predictions where then compared with the obtained estimations for the same epochs, to get a measurement of the prediction error. Linear and quadratic models are investigated, with different fit and prediction intervals. Ten months of real GPS data taken from the IGS were processed. See reference **[1]** for more details about the context and complete outcomes of the experimentation activities carried out.

The following figures show the results obtained for the Block IIR GPS satellites. It is important to mention that analogous results were observed for less stable (and, thus, less predictable) standards, such as cesium and other rubidium clocks not belonging to the Block IIR. The RMS of the prediction error is plotted as a function of the prediction time for different fit intervals. The RMS includes all prediction

windows within the 2-day data span and all the satellites considered. Figures for both linear and quadratic fits are presented:

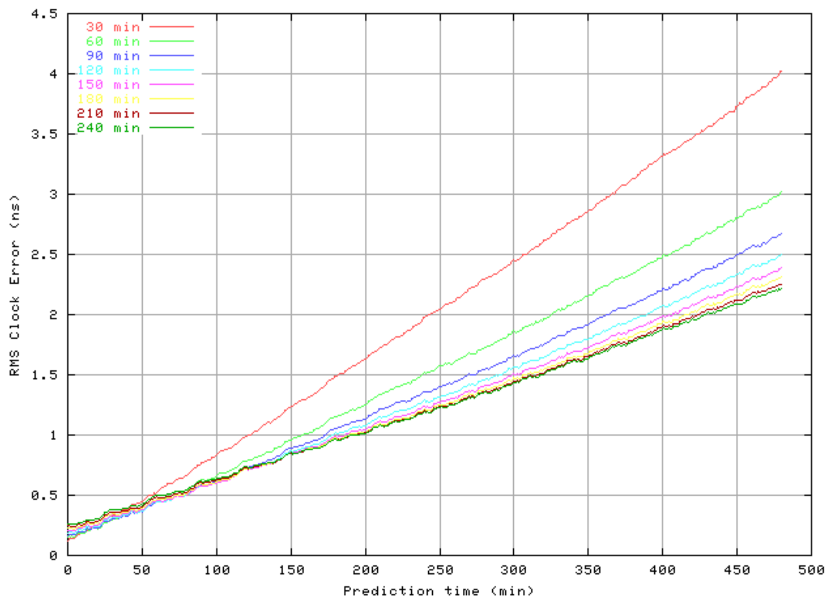

Figure 1. Block IIR clock predictability analysis (linear fit – PRN: 11, 13, 20, 28).

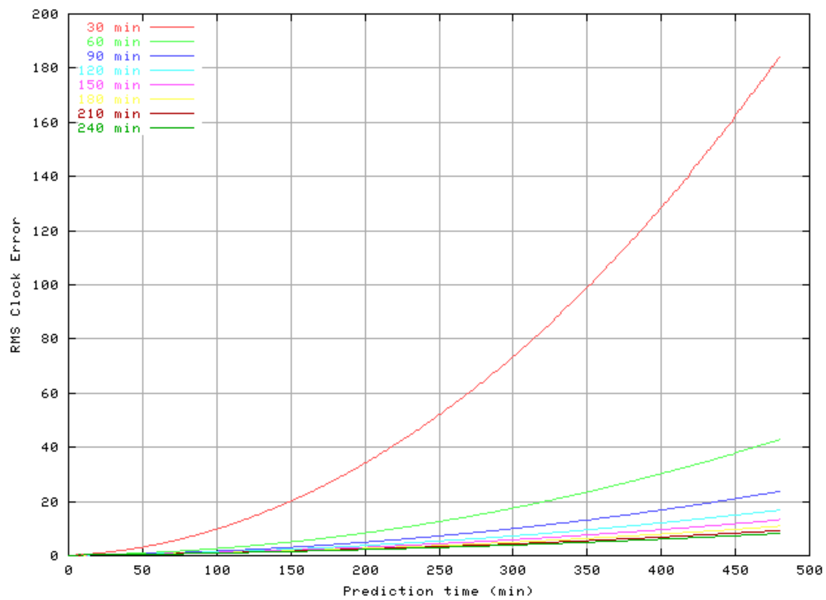

Figure 2. Block IIR clock predictability analysis (quadratic fit – PRN: 11, 13, 20, 28).

From the obtained results it was concluded that:

- The linear model was better than the quadratic one for prediction, above all for long prediction times
- The best results were obtained when at least 2 hours of data are used to fit the clock model.

Step 2: E-OSPF Experimentation

The objective of this experimentation was the assessment of a suitable fit model to be used for generating accurate satellite clocks predictions. As in the Galileo Early Trials, particular attention was put on the Block IIR satellites as the most representative ones for the extrapolation of the conclusions to the Galileo context. Based on the results of the Galileo Early Trials experimentation, all the models considered were based on linear regression fit strategies.

The following models were considered for the analysis:

Linear Model A: The clock estimations in a certain fit interval at the end of the estimation arc are fitted to a linear model (linear regression).

Linear Model B: Two different fit intervals are used: a shorter fit interval is used for computing the independent term of the linear model, whereas a longer one is used for estimating the first-order term.

Linear Model C: As in Linear Model B, two different fit intervals are used. The difference between these models is that, for Linear Model C, the first-order tem of the clock model is built in such a way that, at the beginning of the prediction interval, the model matches the prediction that would have been obtained if it had been generated with Linear Model A for the shorter fit interval, and at the end of the prediction interval, it had been generated with Linear Model A for the longer fit interval. For the sake of clarity, the following two figures have been plotted, depicting how linear models B and C are built:

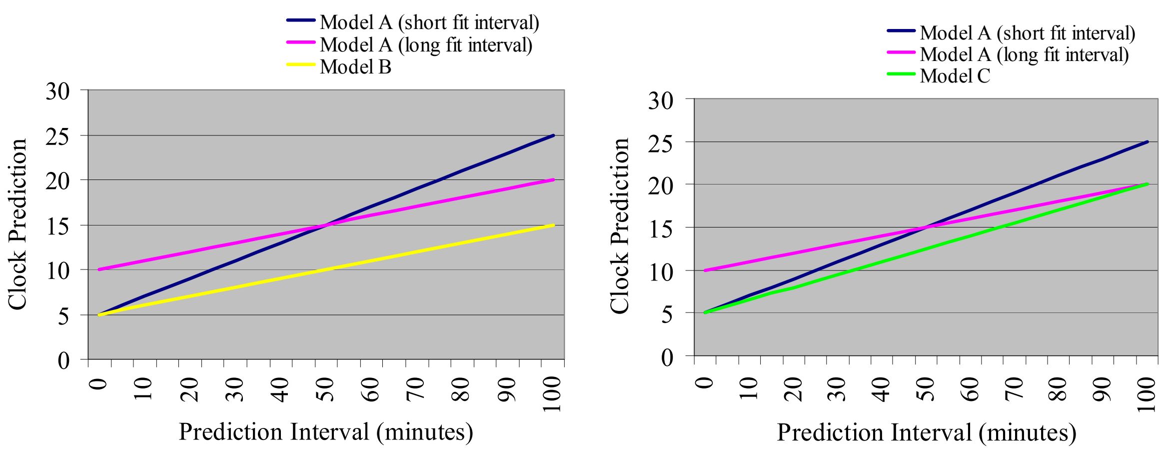

Figure 3. Linear clock model B and linear clock model C.

Linear Model A was tested for 2-hour-long and 14-hour-long fit intervals. Linear Model B was tested for the following two sets of fit intervals: a first combination of 2 hours for the shorter interval and 14 hours for the longer interval, and a second combination of 1 hour for the shorter interval and 6 hours for the longer interval. Linear Model C was tested for a combination of 2 hours for the shorter interval and 14 hours for the longer interval. In all these cases, the clock predictions were generated by extrapolating the models obtained to the time epochs in the prediction interval.

A time period of 11 days was processed for testing the performance that could be obtained with each one of the clock prediction models considered. Clock Prediction error was computed by subtracting the clock

predictions from the GSTB-V1 E-OSPF estimations for the same time epochs. The results obtained (67% and 95% percentiles of the RMS of the obtained clock prediction errors, for Block IIR GPS satellites, at a 100-minute prediction time) are shown in the figure below:

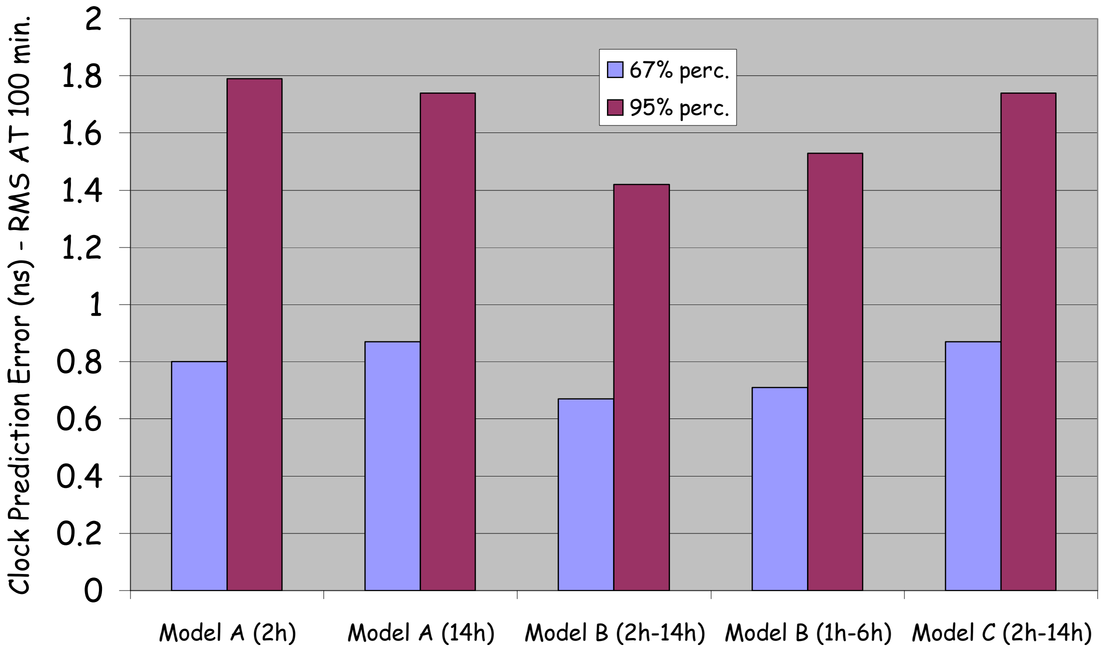

Figure 4. 67% and 95% percentiles (RMS at 100 minutes) of the clock prediction error.

From the obtained results, it was concluded that:

- The best results were obtained for Linear Model B with fit intervals of 2 and 14 hours.
- However, and due to the constraints derived from the OSPF development, Linear Model B with fit intervals of 1 and 6 hours was decided to be recommended to be used for the clock prediction in the FOC scenario. Note that in that scenario clock predictions are generated using the clock estimations computed in the short batches, which are 6 hours long.
- Linear Model B with 2-hour and 14-hour long fit intervals was proposed to be used for the clock prediction in the IOV scenario.

Step 3: Description of the Galileo Preliminary Satellite Clock Model

The deterministic component of the Galileo satellite clock model (the stochastic component is not considered for generating the clock bias predictions) is expressed with a quadratic polynomial model: $b = af_0 + af_1 t + af_2 t^2$, with the following terms:

- b: approximation of satellite clock offset.
- af_0: clock offset (clock phase). Maximum range is [-0.0625, 0.0625] s.
- af_1: clock offset drift (clock frequency). Maximum range is [$-1.5 \cdot 10^{-8}$, $1.5 \cdot 10^{-8}$] s/s.

- af_2: clock drift rate (clock frequency drift). Maximum range[2] is $[-1.2 \cdot 10^{-17}, 1.2 \cdot 10^{-17}]$ s/s^2.
- t: time.

Note that the specified clock drift rate for the Galileo satellites is stronger than the observed one for the GPS Block IIR satellites. The picture below shows the estimation of the GPS satellite G11, for which a frequency drift term of $-1.37 \cdot 10^{-19}$ s/s^2, has been observed, i.e. two orders of magnitude smaller than the maximum clock drift rate specified for Galileo.

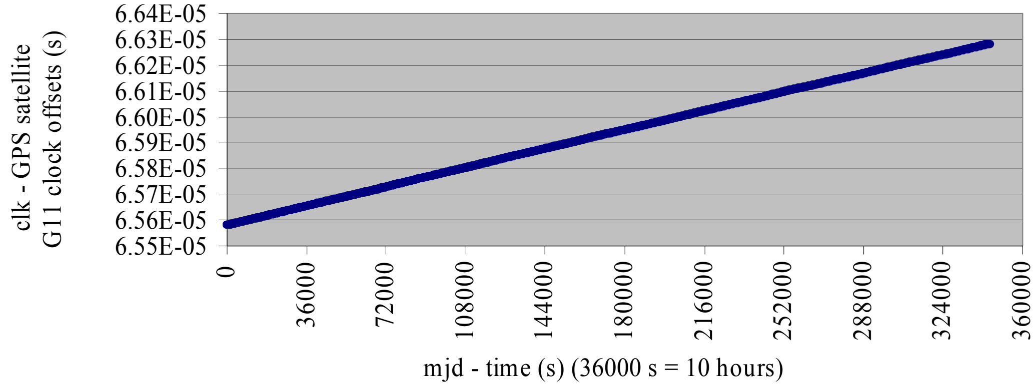

Figure 5. Satellite G11 clock estimation ($af_2 = -1.37 \cdot 10^{-19}$ s/s^2).

Step 4: GSTB-V2 E-OSPF Experimentation

The af_2 term computed for the GIOVE-A satellite (depicted in the figure below) is $5.19 \cdot 10^{-18}$ s/s^2:

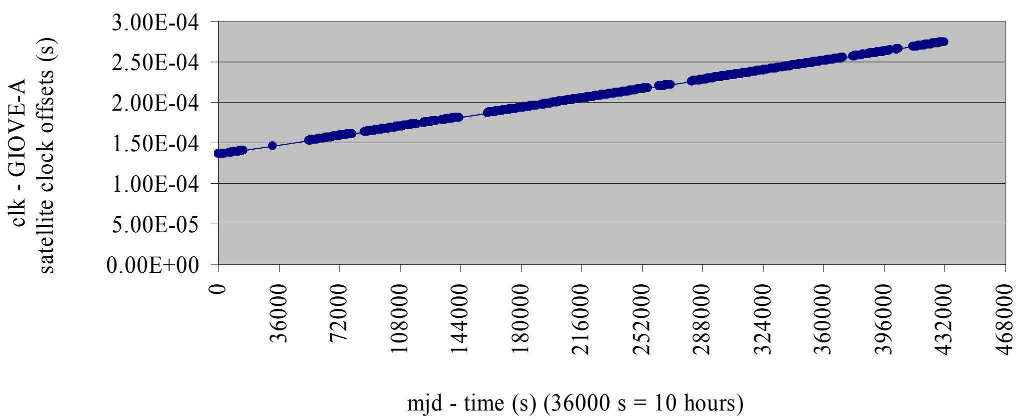

Figure 6. GIOVE-A satellite clock estimation ($af_2 = 5.19 \cdot 10^{-18}$ s/s^2).

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[2] The specified long-term frequency drift for RAFS (Rubidium Atomic Frequency Standard) is $3.65 \cdot 10^{-10}$, which is equivalent to $1.157 \cdot 10^{-17}$ s/s^2 ~ $1.2 \cdot 10^{-17}$ s/s^2.

Step 5: OSPF Experimentation

In view of the expected strong frequency drift behavior of the Galileo satellites, a dedicated analysis had to be performed in the frame of the OSPF experimentation activities, in order to check the observability of the frequency drift parameter and the achievable clock prediction accuracy.

The defined strategy consisted of modifying real GPS clock estimations (with a negligible quadratic behavior) with a frequency drift component, represented by certain af_2 values, for carrying out the intended experimentation.

Analyses have been performed with GPS clock data retrieved from the IGS (International GNSS Service) site, as well as with OSPF estimated clocks. Since the results obtained in the two cases considered are comparable, only results based on the OSPF estimated clocks will be presented.

By using these modified clocks, a trade-off among the following estimation methods was performed:

Baseline model: Linear Model B with fit intervals of a short fit interval of 1 hour, and a long fit interval of 6 hours, as described in the GSTB-V1 E-OSPF Experimentation section. This model has been included not only to compare its results with the second-order fits that will be described in the subsequent bullets, but also to analyze the limit value of the pure parabolic term parameter which makes a difference between the first order fit and the other ones. Remember that this model consisted of fitting a linear model with the last hour of clock estimates for the af0 parameter, and fitting another linear model with the last 6 hours of clock estimates for the af1 parameter.

Conventional parabolic model: Conventional second order, using the same time range for the estimation of all the three coefficients considered. Different estimation arcs of 6, 12, 24, and 48 hours have been tested.

Improved parabolic model: This algorithm is based on the conventional parabolic model, but using different time fit intervals for the estimation of each on of the coefficients of the clock model (af0, af1, af2). In this algorithm, the af0 is fitted using the clock data within the last hour in the estimation period, the af1 using the data from the last 6 hours, and some different arc lengths have been tested for the af2 coefficient estimation (6, 12, 24, and 48 hours).

Parabola-removed model: The af2 term is first estimated with a second-order polynomial fit using different time intervals of 6, 12, 24, and 48 hours. Then a pure parabolic term is subtracted from the clock estimates using the previously calculated af2. This modified clock, with a rather linear trend, is used for the af1 and af0 estimation, by means of two first-order fits consisting of computing the af0 with the last hour in the estimation period, and computing the af1 using the last 6 hours in the estimation period.

The different values for the af_2 coefficient considered for the analysis are:

- $af_2 = 5.5 \cdot 10^{-17}$ s/s^2 representing the maximum allowed af_2 value for Galileo clocks that could be included in the navigation message
- $af_2 = 1.15 \cdot 10^{-17}$ s/s^2, representing maximum af_2 value specified for Galileo clocks
- $af_2 = 2 \cdot 10^{-18}$ s/s^2, which is the af_2 value that could be absorbed by a linear fit without showing a significant performance degradation
- $af_2 = 0$ s/s^2, representing a linear clock, such as observed in GPS Block IIR satellites.

The results obtained for the E-OSPF analysed clocks are shown in the figures below:

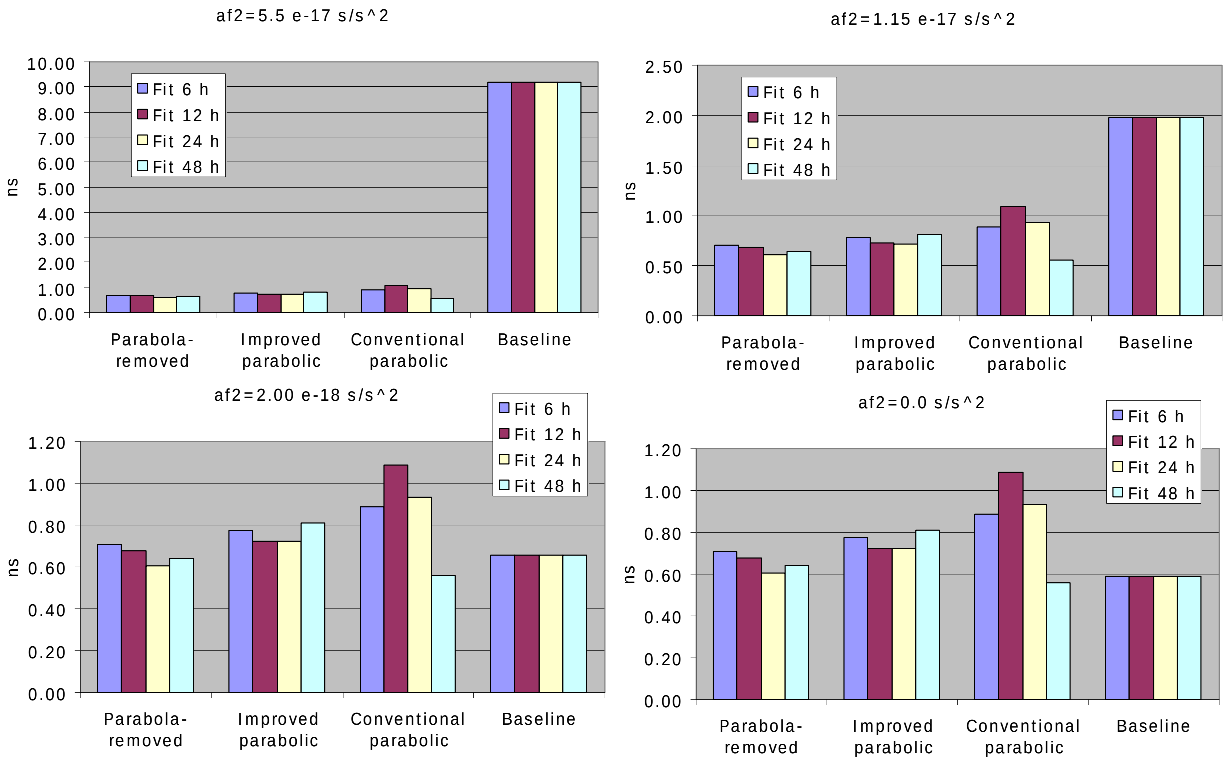


Figure 7. Clock prediction errors for different af2 values, with different fitting methods.

From the results obtained, it can be observed that:

- The "conventional parabolic" method, has shown very good performances, but only better than the other alternatives when a 48-hour-long fit interval has been used. This approximation if not feasible for the OSPF, due its operational constraints (clock predictions are generated in shorter batches).
- The "baseline" method is optimum for clocks with negligible quadratic behavior, whereas it is not convenient at all for clocks with a strong quadratic component.
- The parabolic methods are better than the "baseline" (linear) model, for fitting the clocks with quadratic component. The stronger the quadratic behavior is, the worse the obtained performance are if the "baseline" (linear) method is used.
- Among the three considered parabolic methods, the "parabola-removed" method is the one that provides the best performances, in particular for a 24-hour-long fit interval.
- The performances obtained with the "baseline" method are comparable to those obtained with the parabolic methods only for quadratic components around $2.0 \cdot 10^{-18}$ s/s^2 (~ $6.0 \cdot 10^{-10}$ m/s).

Step 6: Clock Bias Prediction Strategy Definition

In view of the analyses presented in the previous sections, it can be concluded that the recommended approach for performing the clock prediction computations in the OSPF consists of estimating the clock frequency drift of the satellite in order to decide whether to use the "baseline" (linear) model or the "parabola-removed" method for generating the clock prediction. The threshold for the decision has been set at $2.0 \cdot 10^{-18}$ s/s^2.

MASTER AND SLAVE PTFS – DEFAULT AND BACKUP TIME REFERENCES MANAGEMENT

As explained in the previous section, the Clock Prediction algorithm is in charge of fitting the satellite clock estimations to a certain model for a prescribed time-window, in order to obtain the three clock model parameters that will be transmitted to the user in the navigation message.

It is important to notice that, for redundancy purposes, the existence of two PTF (Precise Time Facility) elements has been considered in the design of the Galileo system. One of them has the role of “master” PTF, and the other one has the role of “slave” PTF. A steering process is performed over the “slave” PTF clock in order to keep it aligned with the “master” PTF clock. These roles can be swapped, for example in case some problems were detected in the PTF that is playing the master role, or in case its functioning was required to be interrupted for maintenance purposes, through what is called a “PTF switch.”

The OSPF OD&TS SW can be configured for processing tracking data from both the “master” and “slave” PTF stations. This will be done in the FOC configurations, since:

- the “master” PTF clock is the OSPF OD&TS internal default time reference, and the “slave” PTF clock is used as backup time reference. The OSPF OD&TS satellite clock offsets will be estimated with respect to the backup time reference if malfunctioning or lack of observability from the “master” PTF site are detected by the OD&TS estimator.
- in case of a PTF switch, the OSPF shall use as time reference the newly declared master PTF. In order to ensure a smooth time reference transition, the OSPF shall implement an appropriate transition law during a limited time period after the PTF switch. During this transition period associated with the PTF switch operation, the OSPF is not allowed to degrade its performance.

In the IOV configurations, the OSPF OD&TS SW will also be configured so that the “master” PTF clock is used as internal default time reference, whereas one of the system satellite clocks is recommended to be configured as the backup time reference. This is due to the fact that the location of the two PTF elements, which are physically quite near to each other, does not allow a significant improvement in the observability conditions.

The physical realization of the GST (Galileo System Time) will generally be provided by the master PTF GSS clock. However, since during the transition from the “master” to the “slave” in case of a PTF switch, the OSPF will internally adjust the time reference in order to perform a smooth evolution from the former to the latter, the OSPF time reference, i.e. the GST, will be internally defined by the OSPF.

So the Clock Prediction algorithm has to manage to accomplish with these additional tasks, besides generating the satellite clock predictions models to be integrated in the navigation messages:

- shift all estimated clock offsets which have been estimated with respect to the backup time reference to the correct GST time reference,
- build a transition model, based on the estimated offset between the two PTF elements, to be applied during a certain transition interval, trying to absorb the discontinuity between the time references while maintaining the accuracy, integrity, and availability of the system.

The re-reference function consists of estimating a clock model of the offset between the master and the backup clocks, which has to be added to the clock offsets referred to the latter. This way, all the available clock offsets are expressed with respect to the correct GST time reference. This is particularly important in degraded visibility scenarios, such as in the IOV configurations, for improving the system availability and continuity conditions.

The PTF switch functionality is fairly more complicated and requires its own subsection to be described in further detail.

PTF switch

If a PTF switch has been configured at a certain time, the OD&TS estimator will use the slave PTF as the reference from that moment onwards. In order to ensure that the GST time reference propagated by the navigation message shifts smoothly from the master PTF to the slave PTF, the Clock Prediction algorithm shall correct the estimated and predicted clock by using a suitable model.

Due to the natural evolution of the PTFs, and even though the steering that will be performed for keeping them synchronized, certain phase and frequency offsets will exist between the two references. At the time the command switch arrives, the offset between both PTFs will be able to be modelled as:

$$t_{Mastertswitch} - t_{Slavetswitch} \sim a0 + a1(t - t_{switch}),$$

where:

- a0 is the phase offset between the two PTFs at the time the PTF switch is commanded
- a1 is the frequency offset between the two PTFs at the time the PTF switch is commanded

Because of these initial offsets, the PTF switch cannot be performed by simply selecting the slave PTF clock as the new master clock when the command arrives, since this approach would lead to an abrupt change of the GST reference, which would lead to:

- loss of the GST stability requirements
- inconsistencies between co-existing navigation messages
- additional ranging errors which could cause OSPF integrity failures.

For the above reasons, some correction needs to be applied when the Slave PTF is selected as master clock. The purpose of this correction is to ensure GST continuity and control the extra ranging errors below acceptable limits. The function that describes it is referred to as PTF Switch Law in the OSPF context, which defines the clock correction to be added to keep continuity of the GST reference when the master PTF is abandoned as master GST reference and the slave PTF is used instead following a PTF switch command.

The OSPF approach consists of building a polynomial PTF Switch Law as defined by the following expression:

$$F(t, a_0, a_1, \tau) = a_0 + a_1\tau\left(\frac{t}{\tau}\right) - (3a_0 + 2a_1\tau)\left(\frac{t}{\tau}\right)^2 + (2a_0 + a_1\tau)\left(\frac{t}{\tau}\right)^3$$

where:

- "t" is the time elapsed since the beginning of the PTF switch
- a_0 is the initial phase offset existing between the master and slave PTFs
- a_1 is the initial frequency offset existing between the master and slave PTFs
- τ is the transition characteristic time.

The aforementioned transition function has been defined so that:

- it matches a linear (a_0, a_1) parameter clock model before t0 (start of the PTF switch), so that the initial value of the correction ensures that the clock correction messages are still referred to the master PTF at the beginning of the switch
- its value is zero after the transition period subsequent to the PTF switch epoch, so that when the transition is completed, all new clock messages correspond to the slave PTF with no history of what was the initial offset with the master PTF
- during the PTF switch transition period, the transition function is a third-order polynomial, so that the continuity and the smoothness of the transition are ensured.

To correct the computed clock predictions, though, this function will have to be adjusted to a clock model, which will be added to all of the satellite prediction clock models. This can be easily done by computing the function at all the epochs in the prediction clock interval and by adjusting a clock model, by means of an ordinary regression method, to the obtained clock offsets.

In order to assess the feasibility of the PTF switch law computation and application, a dedicated scenario has been processed with the OSPF SW. The required input data have been generated for a nominal FOC configuration, and a PTF switch has been configured for a certain epoch. In particular, "master" and "slave" PTF clocks fulfilling the alignment requirements of expected phase and frequency offsets between them were available.

The plot below illustrates how the OSPF SW is able to compute and apply the suitable PTF Switch Transition Law. It shows how a smooth transition is performed from one PTF to the other. It can be seen how the FUPa (new master PTF) station clock drifts smoothly from its initial value at the PTF switch epoch, in such a way that, after the 48-hour transition period, it has reached the 0.0 value. In the same way, in can be observed that the DARa station clock (previous reference clock now switched to backup) drifts smoothly from the initial 0.0 value to the value of the offset between the two PTFs at the final epoch of the transition period:

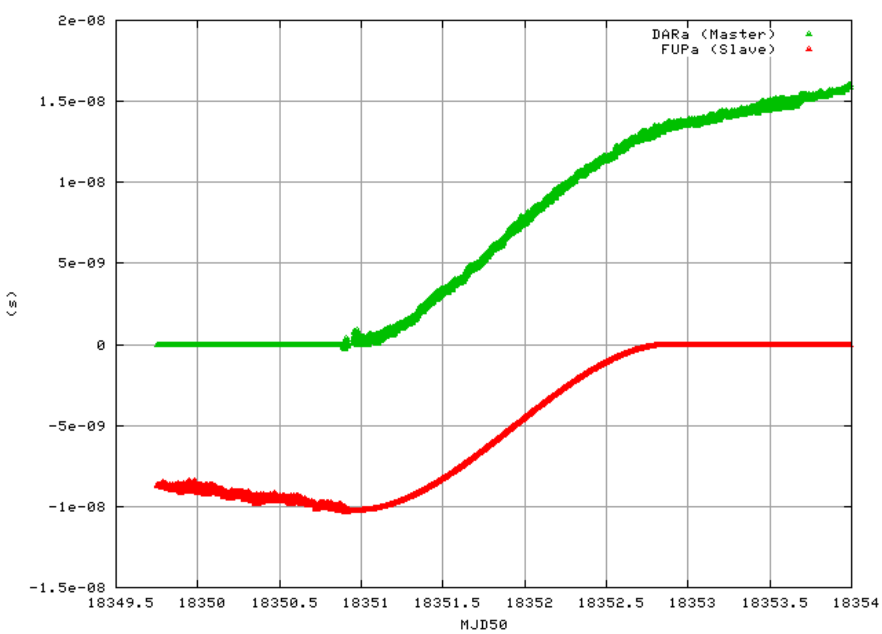


Figure 8. The PTF's smooth variation during the PTF switch transition period (< 48 hours).

4. OSPF PERFORMANCE RESULTS

First, clock estimation and prediction results obtained with the OSPF SW will be presented, for both the FOC and IOV scenarios, when processing both real GPS and Galileo simulated data.

The level of performance achieved is obtained by means of comparing the obtained estimated and predicted clock offsets with respect to IGS final products for the real GPS data cases, and with respect to the simulated reference clock data for the simulated data tests.

REAL GPS DATA CLOCK ESTIMATION AND PREDICTION RESULTS

FOC Scenario

The main characteristics of the GPS real data scenario processed by the OSPF for the FOC environment can be summarized as follows:

- The processed data span covers 10 days, from 1 May till 10 May 2004.
- A total number of 21 GPS satellites have been configured. Among them, the following ones belong to Block IIR: G11, G13, G14, G18, G20, G21, G22 and G28.
- The selected sensor station network is composed of 19 IGS (or GSTB-v1) homogenously distributed sites. USN1 is used as the time reference.

The results obtained for clock estimation and prediction accuracy are shown in the following plots:

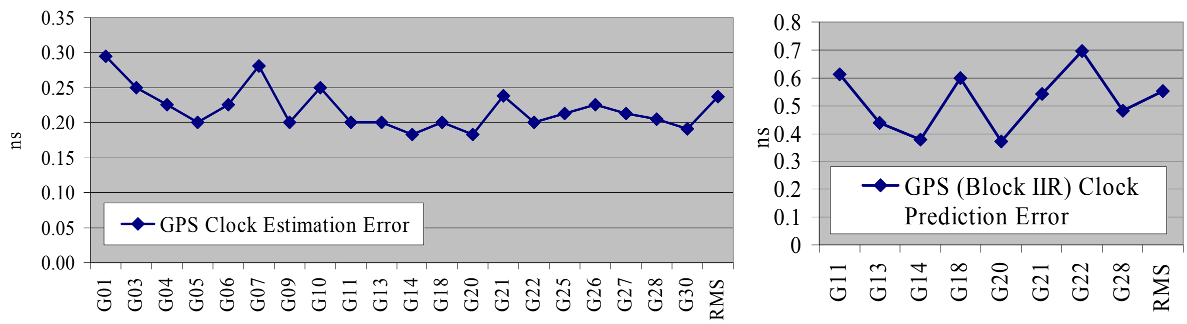


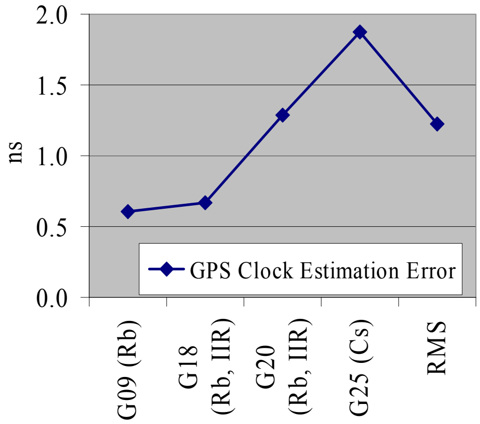
Figure 9. Clock estimation accuracy (RMS over a 6-hour estimation period) and predicted clock accuracy (RMS at a 100-minute prediction epoch) (Block IIR satellites).

IOV Scenario

The main characteristics of the GPS real data scenario processed by the OSPF for the IOV environment can be summarized as follows:

- The processed data span covers 10 days, from 1 May till 10 May 2004.
- A total number of 4 GPS satellites have been configured: G09, G18 G20 and G25, among which G18 and G20 belong to Block IIR. All except for G25 had Rb standards in the period considered.
- The selected sensor station network is composed of 18 IGS (or GSTB-V1) homogenously distributed sites. USN1 is used as the time reference.

The obtained results for clock estimation and prediction accuracy are shown in the plots below. More details about the OSPF SW configuration, and other performance results, can be found in **[2]**.



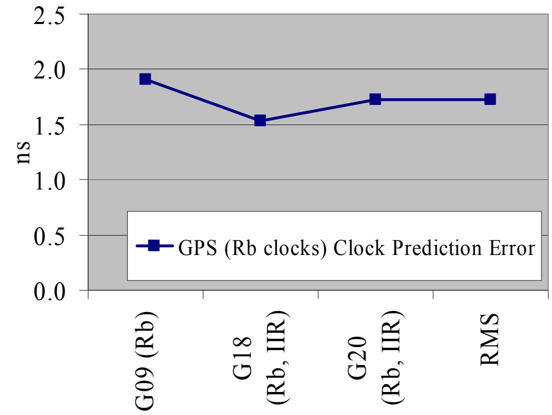


Figure 10. Clock estimation accuracy (RMS over a 24-hour estimation period) and predicted clock accuracy (RMS at a 100-minute prediction epoch).

SIMULATED GALILEO DATA CLOCK ESTIMATION AND PREDICTION RESULTS

FOC Scenario

The main characteristics of the Galileo simulated data scenario processed by the OSPF for the FOC environment can be summarized as follows:

- The processed data span covers 12 days, from 27 March till 7 April 2000.
- The sub-nominal Galileo constellation, composed of 26 satellites, has been configured.
- The selected sensor station network is composed of 28 homogenously distributed GSSs, plus DARa as the "master" PTF and FUPa as the "slave" PTF.

The obtained results for clock estimation and prediction accuracy are shown in the following plots:

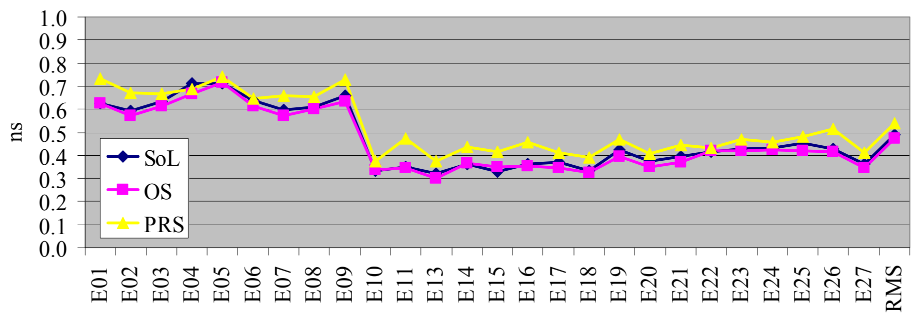


Figure 11. Clock estimation accuracy (RMS over a 6-hour estimation period).

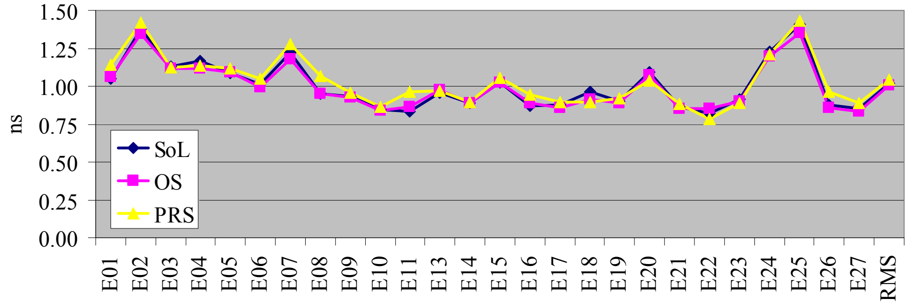


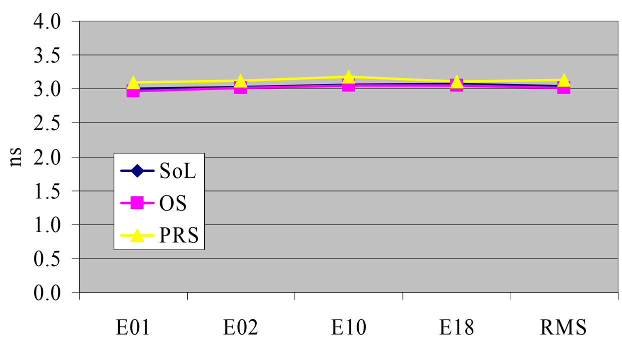
Figure 12. Predicted clock accuracy (RMS at a 100-minute prediction epoch).

IOV Scenario

The main characteristics of the Galileo simulated data scenario processed by the OSPF for the IOV environment can be summarized as follows:

- The processed data span covers 12 days, from 27 March till 7 April 2000.
- A total number of four Galileo satellites have been configured: E01, E02, E10, and E18.
- The selected sensor station network is composed of 18 homogenously distributed GSSs, plus DARa as the time reference station.

The obtained results for clock estimation and prediction accuracy are shown in the following plots:



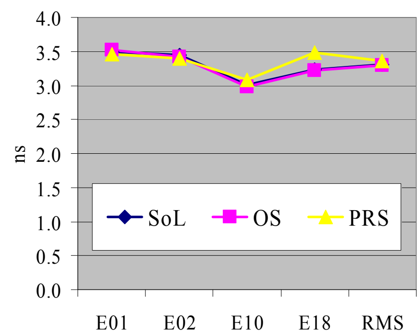


Figure 13. Clock estimation accuracy (RMS over a 24-hour estimation period) and predicted clock accuracy (RMS at a 100-minute prediction epoch).

SIMULATED GALILEO DATA PTF SWITCH SCENARIO CLOCK PREDICTION RESULTS

In order to give some evidence about the fact that the OD&TS product accuracy is maintained during the transition period subsequent to the occurrence of a PTF switch, the clock prediction errors obtained in a certain scenario where a PTF switch has taken place will be shown, compared to the ones obtained in the nominal case, when no PTF switch was commanded. The plot shows the clock prediction errors, obtained when comparing the clock offsets at a 100-minute prediction time, with respect to the clock offsets estimations for the same epochs, measured in a subsequent short arc. Clock predictions for all arcs affected by the PTF switch have been considered, including the PTF switch epoch and transition period.

The figure below shows the RMS (Root Mean Square) of the prediction errors obtained for both the nominal scenario and the PTF switch scenario. Results for all satellites are individually shown, as well as the RMS for all of them. The composition of the RMS of the clock prediction error with the hypothetical error of the clock estimation error (0.32 ns), in line with the clock prediction errors obtained in the analysis of the results generated for the nominal scenario, has also been considered. It can be observed that there is no degradation with respect to the nominal case when a "nominal" PTF switch is performed.

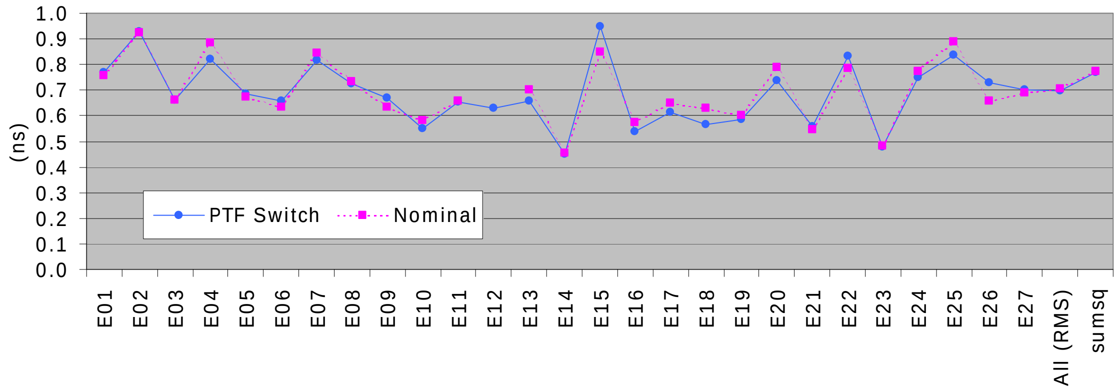


Figure 14. RMS clock prediction error at 100 min.

These results show that in case a PTF switch takes place:

- The OSPF is able to perform a smooth transition from one PTF to the other.
- The transition is performed in such a way that there is no noticeable performance degradation with respect to the nominal case.

5. CONCLUSIONS

The OSPF clock bias estimation is performed in an OD&TS process, based on a state-of-the-art weighted least squares with an *a priori* information filter, which simultaneously updates the orbit and clock parameters.

This strategy allows the existence of a backup time reference to be used in case of lack of observability from the master PTF (Precise Timing Facility). This will be particularly useful in the IOV (In-Orbit Validation) configuration, which will allow the verification of the proper functioning of the overall system before entering the FOC (Full Operation Capability) phase.

The OSPF clock prediction algorithm is in charge of computing the parameters of the clock bias prediction model to be included in the satellite navigation messages transmitted to the users.

The clock estimated offset fitting strategy does take into account the characteristics of the Galileo system clocks, in particular the specified clock drift rate of the Galileo satellite clocks.

The OSPF clock bias prediction algorithm is also able to process a "PTF switch" command, and perform a smooth transition between the two PTF stations clocks without degrading the E-OSPF performance.

Clock estimation and prediction results obtained with the OSPF prototyping platform have been presented, for both the FOC and IOV scenarios, when processing both real GPS and Galileo simulated data. The results presented, together with those obtained for the orbit prediction (see **[2]**), are in line with the navigation performance requirements (1.30 m in FOC, and 3.0 m in IOV for the ranging accuracy).

The results obtained for the GPS scenarios let us be confident of the OSPF design and implementation. Those obtained for the Galileo scenarios show that the OSPF is able to successfully manage the particularities of the Galileo system. The significance of the results obtained depends on the suitability of the RDG (Raw Data Generator) to simulate the real features of the Galileo measurements. The implemented models, which have agreed at system level, are considered to be highly realistic, and also the RDG configuration has been properly tuned for providing representative data. However, the specific values obtained can be considered to be very good clues, but not to the extent of being directly used for quantifying the final performances that will be achieved when the final operational system is deployed.

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6. REFERENCES

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[2] A. B. Martín Peiró, M. D. Laínez, P. F. Navarro, J. Ramon Martin, A. Gavin, F. Amarillo, A. Ballereau, and B. Schlarmann, 2007, "*Characterization of the Navigation Performances in Galileo: E-OSPF SW Experimentation Results,*" in Proceedings of the ION GNSS 2007 Meeting, 25-28 September 2007, Fort Worth, Texas, USA (Institute of Navigation, Alexandria, Virginia), pp. 488-499.